Renewable and Sustainable Energy Reviews 19 (2013) 64–81

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review on passive heat transfer enhancements in pipe exchangers

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ARTICLE INFO

Article history:
Received 21 July 2012
Received in revised form
1 November 2012
Accepted 5 November 2012
Available online 7 December 2012

Keywords:
Passive heat transfer
Twisted tape
Wire coil
Wings
Swirl flow
Ribs
Conical ring

ABSTRACT

Enhancing heat transfer surface are used in many engineering applications such as heat exchanger, air conditioning, chemical reactor and refrigeration systems, hence many techniques have been investigated on enhancement of heat transfer rate and decrease the size and cost of the involving equipment especially in heat exchangers. One of the most important techniques used are passive heat transfer technique. These techniques when adopted in Heat exchanger proved that the overall thermal performance improved significantly. This paper reviews experimental and numerical works taken by researchers on this technique since 2004 such as twisted tape, wire coil, swirl flow generator,... etc. to enhance the thermal efficiency in heat exchangers and useful to designers implementing passive augmentation techniques in heat exchange. The authors found that variously developed twisted tape inserts are popular researched and used to strengthen the heat transfer efficiency for heat exchangers. The other techniques used for specific work environments are studied in this paper. Twisted tape inserts perform better in laminar flow than turbulent flow. However, the other several passive techniques such as ribs, conical nozzle, and conical ring, etc. are generally more efficient in the turbulent flow than in the laminar flow.

Contents

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http://dx.doi.org/10.1016/j.rser.2012.11.021

1. Introduction

Heat exchangers are popular used in industrial and engineering applications. The design procedure of heat exchangers is quite complicated, as it needs exact analysis of heat transfer rate, efficiency and pressure drop apart from issues such as long-term performance and the economic aspect of the equipment. Whenever inserts technologies are used for the heat transfer enhancement, along with the improvement in the heat transfer rate, the pressure drop also increases, which induces the higher pumping cost. Therefore any augmentation device or methods utilized into the heat exchanger should be optimized between the benefits of heat transfer coefficient and the higher pumping cost owing to the increased frictional losses. In general, heat transfer augmentation methods are classified into three broad categories:

1.1. Active method

This method involves some external power input for the enhancement of heat transfer. Some examples of active methods include induced pulsation by cams and reciprocating plungers, the use of a magnetic field to disturb the seeded light particles in a flowing stream, mechanicals aids, surface vibration, fluid vibration, electrostatic fields, suction or injection and jet impingement requires an external activator/power supply to bring about the enhancement [1].

1.2. Passive method

This method generally uses surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. For example, inserts extra component, swirl flow devices, treated surface, rough surfaces, extended surfaces, displaced enhancement devices, coiled tubes, surface tension devices and additives for fluids [2].

1.3. Compound method

Combination of the above two methods, such as rough surface with a twisted tape swirl flow device, or rough surface with fluid vibration, rough surface with twisted tapes [3].

This paper focuses on reviewing the passive methods in pipe heat exchanger. The passive heat transfer augmentation methods as stated earlier do not need any external power input. For the convective heat transfer, one of the ways to enhance heat transfer rate is to increase the effective surface area and residence time of the heat transfer fluids. The passive methods are based on this principle, by employing several techniques to generate the swirl in the bulk of the fluids and disturb the actual boundary layer so as to increase effective surface area, residence time and consequently heat transfer coefficient in existing system. Although there are hundreds of passive methods to enhance the heat transfer performance, the following nine are most popular used in different aspects:

- **Treated Surfaces:** They are heat transfer surfaces that have a fine-scale alteration to their finish or coating. The alteration could be continuous or discontinuous, where the roughness is much smaller than what affects single-phase heat transfer, and they are used primarily for boiling and condensing duties.
- **Rough surfaces:** They are generally surface modifications that promote turbulence in the flow field, primarily in single-phase flows, and do not increase the heat transfer surface area. Their geometric features range from random sand-grain roughness to discrete three-dimensional surface protuberances.
- **Extended surfaces:** They provide effective heat transfer enlargement. The newer developments have led to modified fin surfaces that also tend to improve the heat transfer coefficients by disturbing the flow field in addition to increasing the surface area.
- **Displaced enhancement devices:** These are the insert techniques that are used primarily in confined force convection. These devices improve the energy transfer indirectly at the heat exchange surface by displacing the fluid from the heated or cooled surface of the duct/pipe with bulk fluid to the core flow.
- **Swirl flow devices:** They produce and superimpose swirl flow or secondary recirculation on the axial flow in a channel. These devices include helical strip or cored screw type tube inserts, twisted tapes. They can be used for single phase or two-phase flows heat exchanger.
- **Coiled tubes:** These techniques are suitable for relatively more compact heat exchangers. Coiled tubes produce secondary flows and vortices which promote higher heat transfer coefficient in single phase flow as well as in most boiling regions.
- **Surface tension devices:** These consist of wicking or grooved surfaces, which directly improve the boiling and condensing surface. These devices are most used for heat exchanger occurring phase transformation.
- **Additives for liquids:** These include the addition of solid particles, soluble trace additives and gas bubbles into single phase flows and trace additives which usually depress the surface tension of the liquid for boiling systems.
- **Additives for gases:** These include liquid droplets or solid particles, which are introduced in single-phase gas flows either as dilute phase (gas–solid suspensions) or as dense phase (fluidized beds).

An extensive literature review of all types of heat transfer augmentation technique with external inserts has been discussed by Dewan et al. [4] up to 2004, in the following sections, this paper reviews the subsequently experimental and numerical work on the development of passive heat transfer augmentation techniques by employing twisted tapes, wire coils and ribs, etc insert device.

2. Important definitions terms commonly used in heat transfer augmentation

2.1. Thermal performance factor

Thermal performance factor is generally used to evaluate the performance of different inserts such as twisted tape, wire coil, etc., under a particular fluid flow condition. It is a function of the heat transfer coefficient, the friction factor and Reynolds number. For a particular Reynolds number, if an insert device can achieve significant increase of heat transfer coefficient with minimum raise of friction factor, the thermal performance factor of this device is good.

The overall enhancement ratio is defined as the ratio of the heat transfer enhancement ratio to the friction factor ratio. This parameter is also used to compare different passive techniques for the same pressure drop. The overall enhancement ratio is expressed as:

$$\text{Overall Enhancement Ratio} = \frac{(Nu)/(Nu_0)}{(f/f_0)^{1/3}}$$

where Nu, f, Nu_0 and f_0 are the Nusselt numbers and friction factors for a duct configuration with and without inserts respectively. The friction factor is a measurement of head loss or pumping power.

3. Twisted tape insert devices

Twisted tapes are the metallic strips twisted with some suitable techniques at desired shape and dimension, inserted in the flow. The twisted tape inserts are popular and widely used in heat exchangers for heat transfer augmentation besides twisted tape inserts promote heat transfer rates with less friction factor penalty on pumping power [1–25].

Insertion of twisted tapes in a tube provides a simple passive technique for enhancing the convective heat transfer by introducing swirl into the bulk flow and disrupting the boundary layer at the tube surface due to repeated changes in the surface geometry. That is to say such tapes induce turbulence and superimposed vortex motion (swirl flow) which induces a thinner boundary layer and consequently results in a better heat transfer coefficient and higher Nusselt number due to the changes in the twisted tape geometry. However, the pressure drop inside the tube will be increased by introducing the twisted-tape to insert. Hence a lot of researches have been carried out experimentally and numerically to investigate the optimal design and achieve the best thermal performance with less frication loss. The enhancement of heat transfer using twisted tapes depends on the Pitch and Twist ratio.

The twist ratio is defined as the ratio of pitch to inside diameter of the tube $y = H/d$, where H is the twist pitch length and d is the inside diameter of the tube.

Pitch is defined as the distance between two points that are on the same plane, measured parallel to the axis of a twisted tape.

3.1. Main categories of twisted tape

The most common used twisted tape can be classified into the following seven categories and some of the configuration sketches are displayed in Table 1.

- **Typical twisted tape:** These tapes have length equal to the length of exchanger tube [5,7,9,11,15].
- **Varying length, alternate-axes and pitches twisted tape**: These are distinguished from first category with regards that they are not having the length equal to length of the tube, but half length, $^3/_4$th length and ¼th length of section etc. [8,14,18]; or These are short length tapes with different pitches spaced or twist types connecting to each other with alternate axes [20,22,23].
- **Multiple twisted tapes**: More than one twist tapes are coupled used in one heat exchanger tube [9,23].
- **Twisted tape with rod and varying spacer:** Twisted tape with rod and spacer to enhance the heat transfer rate [9,14,17,29].
- **Twisted tape with attached fins and baffles:** Baffles are attached to the twisted tape at some intervals so as to achieve more augmentation [9,19,20].
- **Twisted tapes with slots, holes, cuts:** Slots and holes of suitable dimensions made in the twisted tape in order to create more turbulence [21–24,30,37].
- **Helical left–right twisted tape with screw**: The twisted tapes are shaped left–right helical and sometimes with screw element [17,18,25,26].
- **Tapes with different surface modifications:** Some insulating material is provided to tapes so that fin effect can be avoided. In some cases surface dimpled material used for tape fabrication [13,30–32].

These literatures presented in Tables 2–4 investigated the effect of typical and developed twisted tapes on the heat transfer performance with different shape, angle and inserting locations at full-length dual and regularly-spaced dual twisted tapes, peripherally-cut twisted tape with serrated-edge insert and delta-winglet twisted tape. The thermal impacts of the oblique delta-winglet twisted tape (O-DWT), straight delta-winglet twisted tape (S-DWT) arrangements, serrated twisted tape (STT) peripherally-cut twisted tape with alternate axis (PT-A) and multiple twisted tape vortex generators (MT-VG) as swirl generators, for different heating fluid and wall condition are investigated. All these investigations indicate the relationships between the enhancement of the heat transfer and the increase of the pressure drop inside the heat exchanger channels [2–30].

3.2. Experimental work

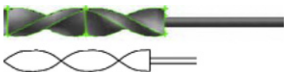
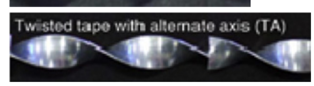
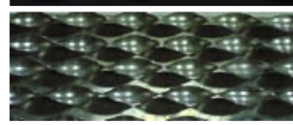
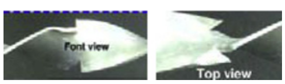
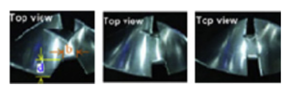
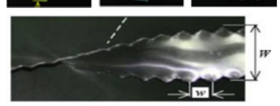
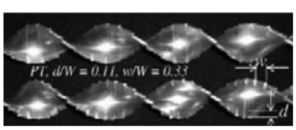
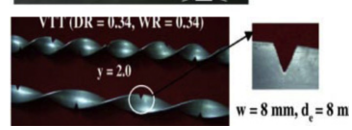
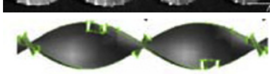
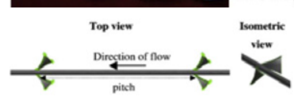
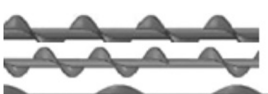
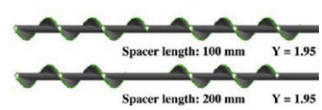
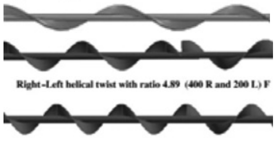
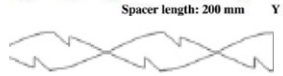
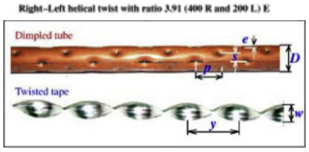
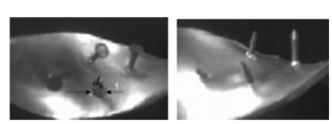
Large number of experimental work are carried out by researchers to investigate the thermohydraulic performance of various twisted tapes including the traditional simple twisted tapes, regularly spaced twisted tapes, varying length twisted tapes, tapes with different cut shapes, tapes with baffles and tapes with different surface modifications. The followings content will detail these reaches and display the finds from different researchers.

3.2.1. Impact of typical twist tapes on the enhancement efficiency

Kumar and Prasad [5], started to investigate the impact of the twist ratio on the enhancement efficiency for a solar water heater. When changed the twist ratios from 3.0 to 12.0 the heat transfer rate inside the solar collectors have been found increased by 18–70%, whereas the pressure drop increased by 87–132%. Synthetically consider the increase of heat transfer and pressure drop it is concluded that the twisted tape enhanced collectors would be preferable for higher grade energy collection to balance the pressure drop rather than for the solar collectors.

Continue research were carried out by Noothong et al. [6] regarding the influences of the twisted tape insertion with a twist ratio of 5.0 and 7.0 in a concentric double pipe heat exchanger. The results revealed that the twisted tape inserts induced the swirl or vortex motions which decrease the boundary layer thickness and enhance the heat transfer rate. The enhancement efficiency, Nusselt number (Nu) and friction factor all are reduced with the decreasing of the twist ratio. Furthermore, Sarada et al. [7], investigated the augmentations of turbulent flow heat transfer in a horizontal tube by varying the width of the twisted tape inserts with

Table 1
Configuration sketches of various twisted tapes.

Configuration	Name	Reference	Configuration	Name	Reference
	Typical twisted tape	[5]		Twisted tape with various widths	[7]
	Twisted tape with various twist ratios	[6]		Short-length twisted tape	[8]
	Left and right twist tape with rod and spacer	[9,14]		Peripherally-cut twisted tape with an alternate axis.	[22]
	Left–right twisted tapes	[18]		Twist tape with alternate axis	[15]
	Dual twisted tapes	[12]		Multiple twisted tape	[13]
	Left and right twisted tape with varying space	[15]		Twisted tape with centre wing	[10]
	Delta-winglet twisted tape	[19]		Twisted tapes with alternate-axes and triangular, rectangular and trapezoidal wings	[20]
	Twisted tape with trapezoidal-cut.	[21]		Serrated twisted tape at various serration depth ratios.	[30]
	Peripherally-cut twisted tape	[23]		V-cut twisted tape insert	[24]
	Jagged twisted tape	[37]		Butter fly inserts	[37]
	Helical screw-tape with varying spacers	[25]		Helical screw tape with various spacer length	[28]
	Right and left helical screw tape	[27]		Twisted-tape with oblique teeth	[37]
	Dimpled tube fitted with twisted tape	[32]		Twisted tape consisting wire nails	[31]

air as the working fluid. When the widths changed from 10 mm to 22 mm, the heat transfer rate are improved by 36% to 48% for the full width=26 mm. This is because of that the centrifugal forces generate the spiral motion of the fluid.

3.2.2. Impact of twisted tape with alternate-axes, varying length and pitches on the enhancement efficiency

The alternate-axes, length and insert position of the twisted tape have differences enhancement effect on the heat transfer, hence researchers have carried out a lot researches [8–11]. Eiamsa-ard et al. [8], studied the impact of the length of twist tape (LR) on the thermal performance, they found that: (1) the presence of the tube with short-length twisted tape insert yields higher heat transfer rate (*Nu*) up to 1.16, 1.22 and 1.27 times of the plain tube, while the friction factor up to 1.76, 1.88 and 1.99 times by applying LR=0.29, 0.43 and 0.57, respectively; (2) the maximum heat transfer (*Nu*) and friction factor (*f*) is obtained for using the full-length tape; (3) the *Nu* and *f* values of the short-length twisted tape insert with LR=0.29, 0.43 and 0.57, respectively, are about 14%, 9.5%, and 6.7%, and 21%, 15.3%, and 10.5% lower than these of the full-length twist tape.

Jaisankar et al. [9] compared the heat transfer enhancement of full length and twisted twist fitted with rod and spacer. It is determined that the first has better effect than second. Some researchers such like Eiamsa-ard et al. [10], combined the alternate-axes and wings techniques together. They found that the twisted tape with alternate axes at the largest angle of attack

Table 2
Experimental works on the thermohydraulic performance of twisted tape enhancement.

Authors	Working fluid	Configuration	Conditions	Observation
Kumar and Prasad [5]	Water	Typical twisted tape (TT)	$4000 \le Re \le 21000$, Twist ratios $y=3.0$–12.0	• Decreasing values of the twist-pitch to tube diameter ratio lead to increasing values of heat transfer rate, and the pressure drop as well • Twisted-tapes generate turbulency superimposed with swirlness inside the flow tube and consequently result in enhanced heat transfer • Increase in twisted-tape solar water heaters performance is remarkable at low and moderate values of the flow Reynolds number and monotonous at high values of the Reynolds number
Noothong et al. [6]	Water	Typical twisted tape (TT)	Twist ratios $y=5.0$ and 7.0 $2000 \le Re \le 12000$	• Swirl flow helps decrease the boundary layer thickness of the hot air flow and increase residence time of hot air in the inner tube • The enhancement efficiency and Nusselt number increases with decreasing the twist ratio and friction factor also increases with decreasing the twist ratio • Secondary fluid motion is generated by the tape twist, and the resulting twist mixing improves the convection heat transfer
Sarada et al. [7]	Air	Typical twisted tape (TT)	Widths of the twisted tapes range from 10 to 22 mm $6000 \le Re \le 13500$	• The enhancement of heat transfer with twisted tape inserts as compared to plain tube • This enhancement is mainly due to the centrifugal forces resulting from the spiral motion of the fluid
S. Eiamsa-ard et al. [8]	Air	Full and short length twisted tape.	$4000 \le Re \le 20000$	• The presence of the tube with short-length twisted tape insert yields higher heat transfer rate
Jaisankar et al. [9]	Water	Full length left–right twist, fitted with rod and spacer at the trailing edge for lengths of 100, 200 and 300 mm	Twist ratios $y=3.0$ and 5.0 $700 \le Re \le 1600$	• The heat enhancement in full length twisted tape is better than the twist fitted with rod and spacer. The decrease in heat transfer augmentation in twist fitted with rod is minimum compared to twist fitted with spacer. The decrease in friction factor is higher for twist fitted with spacer compared to twist fitted with rod
Eiamsa-ard et al., [10]	Water	Twisted tape with wings alone (WT). Twisted tape with alternate axes alone (T-A). Typical twisted tape (TT)	Twist ratio $y=3.0$. Angles of attack $\beta=43^{\circ}$, $53^{\circ}$and 74° $5200 \le Re \le 22000$.	• WT-A with the largest angle of attack gave the highest Nusselt number (Nu), friction factor (f) as well as thermal performance factor
Wongcharee and Eiamsa-ard [11]	Water	Alternate clockwise and counter-clockwise twisted-tapes (TA)	$830 \le Re \le 1990$, Twist ratios $y=3.0$, 4.0 and 5.0	• The friction factor associated by TA is higher than that induced by TT, and friction factor increases with decreasing twist ratio
Eiamsa-ard et al. [12]	Air	Dual twisted tapes	$4000 \le Re \le 19000$, Twist ratios $y=3.0$, 4.0 and 5.0.	• The smaller space ratio of the dual twisted tapes in tandem is more attractive in heat transfer application due to higher enhancement efficiency than the single one
Eiamsa-ard [13]	Air	Multiple twisted tape vortex generators (MT-VG).	$2700 \le Re \le 9000$.	• The decreases of both free-spacing ratio (s/w) and twist ratio (y/w) results in the increases of Nusselt number, friction factor and also enhancement index
Jaisankar et al. [14]	Water	Twist fitted with rod	Twist ratios $y=3.0$ and 5.0	• The heat enhancement is always higher in twisted tape
Jaisankar [17]	Water	Helical and left–right twisted tapes.	Twist ratio $y=3.0$	• The heat enhancement in helical and left–right twisted tape collectors is found to be better than the plain tube collector. While comparing the left–right and helical twisted tape collector for the same twist ratio 3, higher heat transfer and thermal performance are obtained in left–right twisted tape collector
Murugesan et al. [21]	Water	Trapezoidal-cut	$2000 \le Re \le 12000$, Twist ratios $y=4.4$ and 6.0	• The mean Nusselt number for trapezoidal -cut twisted tape higher than typical twisted tape
Eiamsa-ard et al. [19]	Water	Oblique delta-winglet twisted tape (O-DWT) and straight delta-winglet twisted tape	$3000 \le Re \le 27000$, Twist ratios $y=3.0$, 4.0 and 5.0. Depth of wing cut ratios	• The values of Nusselt number and friction factor in the test tube equipped with delta-winglet twisted tape are noticeably higher than those in the plain tube and also tube equipped with typical twisted tape

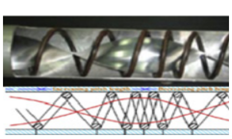
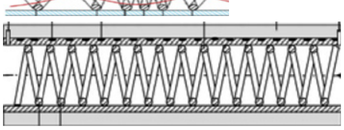
Table 2 (*continued*)

Authors	Working fluid	Configuration	Conditions	Observation
		(S-DWT). Uniform wall heat flux tube	(DR=d/w=0.11, 0.21 and 0.32)	• Nusselt number and friction factor increase with decreasing of twist ratio and increasing depth of wing cut ratio (DR) for all Reynolds numbers studied • O-DWT gives higher Nusselt number and friction factor than that of the S-DWT. The thermal performance factor in the tube with O-DWT is greater than that with S-DWT and the factor increases with decreasing Reynolds number and increasing twist ratio • DWT performs better heat transfer enhancement than that typical twisted tape • DWT can be replaced any of the TT efficiently to reduce the size of the heat exchanger
Wongcharee and Eiamsa-ard [20]	Water	Twisted tapes with wing shape including triangle, rectangle and trapezoid	$5500 \leq Re \leq 20200$, Wing-chord ratios (d/W) of 0.1, 0.2 and 0.3, Twist ratio (y/W) of 4.0.	• The twisted tapes consisted of both alternate-axes and wings offer superior heat transfer enhancement compared to the one with only alternate-axes and also the typical one. This is due to the combined effects of the strong collision of fluid behind the alternate point, caused by alternate axis and the extra fluid disturbance near tube wall induced by wings
Seemawute and Eiamsa-ard [22]	Water	Peripherally-cut twisted tape with alternate axis (PT-A)	$5000 \leq Re \leq 20000$ uniform heat flux circular tube	• Thermal performance in a tube fitted with PT-A are consistently higher than those in the tube equipped with PT, TT and also in the plain tube
Eiamsa-ard et al. [23]	Water	Peripherally-cut twisted tape	$1000 \leq Re \leq 20000$, Twist ratio y=3.0	• The peripherally-cut twisted tape offered higher heat transfer rate, friction factor and also thermal performance factor compared to the typical twisted tape. An additional turbulence of fluid in the vicinity of the tube wall and vorticity behind the cuts generated by the modified twisted tape are referred as the reason for a better heat transfer enhancement
Eiamsa-ard and Promvonge [30]	Air	Serrated twisted tape (STT)	$4000 \leq Re \leq 20000$, Twist ratio y=4.0	• The STT gives higher heat transfer rate than the TT while yields higher friction factor than the TT
Murugesan et al. [31]	Water	Twisted tape consisting wire nails (WN-TT)	$2000 \leq Re \leq 12000$, Twist ratios y=2.0, 4.4 and 6.0	• The better performance of WN-TT is due to combined effects of the following factors: 1) common swirling flow generated by P-TT 2) additional turbulence offered by the wire nails
Jaisankar et al. [20]	Water	Helical twisted tape	Twist ratios y =3.0, 4.0, 5.0 and 6.0	• Thermal performance of twisted tape collector with minimum twist ratio (Y= 3) is better than the other twist ratios
Ibrahim [23]	Water	Helical screw element	$570 \leq Re \leq 1310$ y=2.17, 3.33, 4.3, and 5	• The averaged Nusselt number, Nu increase with the increase in Reynolds number and with the decrease in twist ratio and spacer length
Murugesan et al. [24]	Water	V-cut twisted tape	$2000 \leq Re \leq 12000$	• The V-cut twisted tape offered a higher heat transfer rate, friction factor and also thermal performance factor compared to the plain twisted tape. In addition, the influence of the depth ratio was more dominant than that of the width ratio for all the Reynolds number • The thermal performance factors for all the cases are more than one indicating that the effect of heat transfer enhancement due to the enhancing tool is more dominant than the effect of the rising friction factor and vice versa • Nusselt number and the mean friction factor in the tube with V-cut twisted tape (VTT) increase with decreasing twist ratios (y), width ratios (WR) and increasing depth ratios (DR)
Moawed [25]	Water	Helical screw element	$570 \leq Re \leq 1310$	• The averaged Nusslet number Nuincreases with an increase in the Reynolds number and with a decrease in Y and S • The Nu of the plain elliptic tube is greater than that of the plain circular tube and the Nu of elliptic tubes containing a helical screw tapes is better than that of the plain elliptic tubes for all Re, Y, and S

Table 2 (*continued*)

Authors	Working fluid	Configuration	Conditions	Observation
Sivashanmugam and Nagarajan [27]	Water	Right–left helical screw inserts of equal length	$200 \le Re \le 3000$ $y = 2.93–4.89$	• The heat transfer coefficient enhancement for right–left helical screw inserts is higher than that for straight helical twist for a given twist ratio
Sivashanmugam and Suresh [28]	Water	Full-length helical screw element of different twist ratio	$v = [0.1 \times 10^{-3}$ to $2.4 \times 10^{-3}]$ m^3/min	• There is no much change in the magnitude of heat transfer coefficient enhancement with decreasing twist ratio and with increasing twist ratio, as the intensity of swirl generated at the inlet or at the outlet in the order of increasing twist ratio or decreasing twist ratio, is same in both the cases
Krishna et al. [29]	Water	Straight full twist	Twist ratio $y = 4.0$	• The heat transfer coefficient increases with Reynolds number and decreasing spacer distance with maximum being 2 in. spacer distance for both the type of twist inserts. Also, there is no appreciable increase in heat transfer enhancement in straight full twist insert with 2 in. spacer distance
Thianpong et al. [32]	Water	Dimpled tube fitted with a twisted tape swirl generator	$12000 \le Re \le 44000$, Twist ratios $y = 3.0$, 5.0, and 7.0	• A dimpled tube in common with a twisted tape has significant effects on the heat transfer enhancement and friction factor. The heat transfer and friction factor are increase with decreasing both of pitch ratio (PR) and twist ratio (y/w)
Saha [33]	air	Twisted-tape inserts with and without oblique teeth	$10000 \le Re \le 100000$	• Full-length and short-length twisted-tapes with oblique teeth in combination with axial corrugations show only marginal improvements over the twisted-tapes without oblique teeth

Table 3
Configuration sketches of various wire coils various.

Configuration	Name	Reference	Configuration	Name	Reference
	Coiled square wires	[40]		Twisted tape and wire coil	[42]
	Non-uniform wire coil combined with twisted tape	[43]		Triangle cross sectioned coiled wire	[44]
	Coiled wire turbulators	[39]		Wire coil in pipe	[46]

will provide the highest Nusselt number, friction factors and thermal performance.

Meanwhile, Wongcharee and Eiamsa-ard [11], further investigated the heat enhancement performance of clockwise and counter-clockwise alternate-axes twisted tape (T-A). The results indicate these: (1) the friction factor associated by T-A is higher than that induced by typical twisted tape (TT), and friction factor increases with the decrease of the twist ratio; (2) the friction factors of the tube with the T-A at $y = 3.0$, 4.0 and 5.0 are respectively around 50%, 49% and 33% higher than those of the tube with the TT at the same twist ratio; (3) under the similar condition, the *Nu* associated by T-A is significantly higher than that associated by TT; (4) in the examined range, T-A yield higher *Nu* than TT by around 70.9% to 104.0%, in addition, *Nu* increases with the decreasing of twist ratio such like the T-A with twist ratio of 3.0 provides higher transfer rate than the T-A with twist ratio of 4.0 and 5.0 by 15.6% and 30.7%, respectively.

3.2.3. *Impact of multi twisted tapes on the enhancement efficiency*

From the previous research it is obvious that the twisted tape can improve the heat transfer efficiency, following this finds, Eiamsa-ard et al. [12] investigated the effect of dual and multiple twisted tape impacts on the heat transfer enhancement. The heat transfer rate for the dual twisted tapes is increased by 12% to 29% in comparison with the single tape at the twist ratios from 3.0 to 5.0 by generating strongly dual swirling flows inside the test tube. Depending on the flow conditions and twist ratio y, the increases in heat transfer rate over the plain tube are about 146%, 135% and 128% for $y = 3.0$, 4.0 and 5.0, respectively. The smaller space ratio of the dual twisted tapes in tandem is more attractive in heat transfer application due to the higher enhancement efficiency than the single one. The multiple twisted tape vortex generators (MT-VG) were researched by Eiamsa-ard et al. [13]. The Nusselt numbers increase by 10% to 170% comparing with the values for

Table 4
Experimental works on the thermohydraulic performance of wire coils enhancement.

Authors	Working fluid	Configuration	Conditions	Observation
Gararcia et al. [38]	Water propylene glycol mixtures	• $1.17 \le p/d \le 2.68$ [helical pitch] • $0.07 \le e/d \le 0.10$ [wire diameter]	• $80 \le Re \le 90000$ • $2.8 \le Pr \le 150$	• In laminar flow, results show that wire coils behave mainly as a smooth tube • In turbulent flow, wire coils cause a high pressure drop increase which • depends mainly on pitch to wire-diameter ratio p/e
Yakut and Sahin [39]	Air	• Coiled wire cross Section 4mm • coiled wire length 1240 mm	• $5000 \le Re \le 35000$ • Pitches (10, 20, 30 mm)	• Vortex characteristics of the turbulators should be considered as a selecting criterion with heat transfer and friction characteristics in heat transfer enhancement applications
Promvonge [40]	Air	• wires with square cross section	• $5000 \le Re \le 25000$	• The Nusselt number augmentation tends to decrease rapidly with the rise of Reynolds number • The coiled square wire should be applied instead of the round one to obtain higher heat transfer and performance, leading to more compact heat exchanger
Promvonge [41]	Air	• Coiled wires in conjunction with a snail-type swirl generator	• $5000 \le Re \le 25000$	• The use of the coiled wires and the snail entry causes a high pressure drop
Promvonge [42]	Air	• wire coils in conjunction with twisted tapes	• $3000 \le Re \le 18000$	• Nusselt number augmentation tends to decrease with the rise of Reynolds number • The combined wire coil and twisted tape turbulators are compared with a smooth tube at a constant pumping power. Heat transfer performance is doubled at low Reynolds number • The best operating regime for combined both the turbulators is found at lower Reynolds number values for the lowest values of the coil spring pitch and twist ratio
Eiamsa-ard et al. [43]	Air	• Combined devices of the twisted tape (TT) and constant/periodically varying wire coil pitch ratio	• $4600 \le Re \le 20000$	• At low Reynolds number, the compound devices of the TT with $Y=3$ and the DI-coil, provide the highest thermal performance
Gunes [44]	Air	• Pitch ratios ($P/D=1$, 2 and 3) • ($a/D=0.0714$ and 0.0892)	• $3500 \le Re \le 27000$	• The equilateral triangle cross sectioned coiled wire inserted separately from the tube wall and the coiled wire inserts induced a remarkable increase in both pressure drop and heat transfer in comparison with the smooth tube depending on coil pitches and wire thickness
Akhavan-Behabadi et al. [45]	Oil	• Seven coiled wires having pitches of 12–69 mm	• $10 \le Re \le 1500$	• Wire coil inserts with lower wire diameters have better performance, especially at low Reynolds numbers. Also, the increase in the coil pitch made a moderate decrease in performance parameter

the smooth channel, while the friction factors are 1.45 to 5.7 times of those of the smooth channel.

3.2.4. Impact of twisted tape with rod and varying spacers on the enhancement efficiency

The spacer distance will be another factor influencing the enhancement performance. Jaisankar et al. [14], and Krishna et al. [15] discovered that the heat enhancement in full length twisted tape is better than the twist fitted with rod and spacer; the decrease in heat transfer augmentation in twist with rod is minimum compared to twist with spacer; the decrease in friction factor is maximum for twist with spacer compared to twist with rod; and there is no appreciable increase in heat transfer enhancement in straight full twist insert with 2 in. spacer distance; meanwhile, Jaisankar et al. also proved that there was 17% and 29% decrease of heat transfer with rod and spacer comparing to full length twist [16–18].

3.2.5. Impact of tape with attached fins and baffles on the enhancement efficiency

Usually, the wings, fins and baffles are attached alone the centre line like shown in Table 1, or twisted tapes with wing shaped into triangle, rectangle and trapezoid [10,19,20]. Researchers such like Eiamsa-ard et al. [10] studied the twisted tapes consisting of centre wings and alternate-axes (WT-A). The effect of attack along the centre line of the tape was studied. The results show that the heat transfer rate increases with the increasing of attack angle. Because the superior performance of the WT-A over those of the other tapes could be attributed to the combined effects of the following actions: a common swirling flow induced by the twisted tape; a vortex generated by the wing and a strong collision of the recombined streams behind each alternate point. This research group also investigated the thermal impact of oblique delt-winglet twisted tape (O-DWT) and straight delta-winglet twisted tape (S-DWT). The values of Nusselt

number and friction factor in the test tube equipped with delta-winglet twisted tape are noticeably higher than those in the plain tube and also tube equipped with typical twisted tape. The Nusselt number and friction factor increase with the decreasing of twist ratio and the increasing of the depth of wing cut ratio (DR); O-DWT gives higher Nusselt number and friction factor than that of the S-DWT; the thermal performance factor in the tube with O-DWT is greater than that with S-DWT and the factor increases with the decreasing of Reynolds number and the increasing of twist ratio; DWT performs better heat transfer enhancement than the typical twisted tape, and it indicates that the heat exchanger fitted with DWT is more compacted than the one with the typical twisted tape; therefore DWT can efficiently replace any of the TT with reduced heat exchanger size.

Different from Eiamsa-ard et al. [19], Wongcharee and Eiamsa-ard [20] studied several of wing shape with alternate-axes instead of the depth of the wing, including triangle, rectangle and trapezoid. This group found these: (1) flow visualization by dye technique shows that apart from a common swirl flow, the twisted tapes with alternate axes and wings induce an additional fluid disturbance, signifying the excellent fluid mixing; (2) the twisted tapes consisted of both alternate-axes and wings offer superior heat transfer enhancement compared to the one with only alternate-axes and also the typical one, which thanks to the combined effects of the strong collision of fluid behind the alternate point, caused by alternate axis and the extra fluid disturbance near tube wall induced by wings; (3) for the twisted tapes with combined alternate axes and wings, the tape with trapezoidal wings provides the highest Nusselt number, friction factor as well as thermal performance factor, followed by the one with rectangular.

3.2.6. *Impact of twisted tape with slots, holes, cuts on the enhancement efficiency*

Slots, holes and cuts in the twisted tape can induce disturbance and swirling into the bulk flow, disrupt the laminar low, and increase the *Nu* number and the heat transfer rate. It has been proved by several researchers that this enchantment technology will result in better heat transfer and fluid flow characteristics [12,21–24]. Eiamsa-ard et al. [12] investigated the influences of peripherally-cut twisted tape insert on heart transfer and thermal performance characteristics in laminar and turbulent tube flows. They discovered these: (1) the peripherally-cut twisted tape offered higher heat transfer rate, friction factor and also thermal performance factor compared to the typical twisted tape; (2) an additional turbulence of fluid in the vicinity of the tube wall and vorticity behind the cuts generated by the modified twisted tape contribute to the better heat transfer enhancement; (3) Nusselt number, friction factor as well as thermal performance factor associated by the peripherally-cut twisted tape were found to be increased with the increase of the tape depth ratio (DR) or the decrease of the tape width ratio (WR).

Murugesan et al. [21] carried out a study of the heat transfer and pressure drop characteristics of turbulent flow in a tube fitted with a full length twisted tape coupled with trapezoidal-cut. The results show that for the twist ratio of 6.0, the mean Nusselt number and fanning friction factor for the trapezoidal-cut twisted tape are 1.37 and 1.97 times over the plain tube, respectively. When the twist ratio reduces to 4.4, the corresponding Nusselt number and fanning friction factor will increased to 1.72 and 2.85 times. These indicate that trapezoidal-cut induces significant enhancement of heat transfer coefficient and friction factor, in addition the impact will be heavier for a lower twist ratio. Meanwhile, Seemawute and Eiamsa-ard [22,23] studied the combined impact of peripherally-cut twisted tape with alternate axis (PT-A) on the thermohydraulics of turbulent flow through a round tube. Thermal performance in a tube fitted with PT-A are consistently higher than those in the tube equipped with PT, TT and also in the plain tube. The combined actions induced by the PT-A are responsible for the improvement of heat transfer rate and friction factor by around 50% to 184% and 6 to 11 times, respectively compared to those in the plain tube. Following the trapezoidal-cut and peripherally-cut, Murugesan et al. [24] investigated the effect of V-cut twisted tape insert on heat transfer, friction factor and thermal performance factor characteristics in a circular tube were investigated. The V-cut twisted tape offered a higher heat transfer rate, friction factor and also thermal performance factor rather than the plain twisted tape; in addition, the impact of the depth ratio was more dominant than that of the width ratio for all the Reynolds number; the thermal performance factors for all the cases are more than one indicating that the effect of heat transfer enhancement due to the enhancing tool is more dominant than the effect of the rising friction factor and vice versa.

3.2.7. *Impact of helical twisted tape on the enhancement efficiency*

Helical twisted tape is another kind of developed twisted tape to enhance the heat transfer rate inside the tube or pipe heat exchangers [18,25–28]. Ibrahim [25] studied the heat transfer and friction factor characteristics in the horizontal double pipes flat tubes. With full length of helical screw element, different twist ratio and spacer length were researched. The study shows that, the Nusslet number (*Nu*) and friction factor (f) decrease with the increase of twist ratio (y) value of the flat tube. Furthermore, Moawed [26] investigated thermal influence of helical twisted tape on the elliptic tubes at different twist ratios y and pitch ratios under laminar flow condition. The results indicate that the average Nusslet number increases with the increase of the Reynolds number and the decrease of twist ratio; the Nusslet number of the plain elliptic tube is greater than that of the plain circular tube and the *Nu* of elliptic tubes containing a helical screw tapes is better than that of the plain elliptic tubes for all *Re*, twist ratio.

Sivashanmugam and Nagarajan [27,28] studied circular tube fitted with right–left helical screw inserts of equal length, unequal length of different twist ratio and full-length helical screw element at different twist ratio. The results show that the heat transfer coefficient enhancement for right–left helical screw inserts is higher than that for straight helical twist at a given twist ratio. For full-length helical screw element there is no much change of the heat transfer coefficient enhancement by increasing or decreasing the twist ratio, as the magnitude of swirl generated at the inlet or at the outlet is the same in the both of two cases. Krishna et al. [29] is another investigator group of these interesting enhancement technologies. They found these:

- The heat enhancement in helical and left–right twisted tape collectors is better than the plain tube collector.
- While comparing the left–right and helical twisted tape collector at the same twist ratio of 3.0, higher heat transfer and thermal performance are obtained from the left–right twisted tape collector.
- The increase of heat transfer and friction factor in left–right twisted tape collector is 3.75 and 1.42 times higher than plain tube collector, respectively.
- The solar water heater with left–right twisted tape presents better heat transfer and overall thermal performance than that with the helical twisted tape.

3.2.8. *Impact of twisted tapes with granulated surfaces on the enhancement efficiency*

The reference papers [30–33] introduced another heat transfer enhancement technology, modified twist tape surface. The paper

[30] presents a technology combined the cut and granulation, which is willing to induce more flow turbulent and break down the laminar flow layer with the willing to achieve higher heat transfer rate. With the surface granulation idea, Thianpong et al. [32], studied the friction and compound heat transfer behaviours in a dimpled tube fitted with a twisted tape swirl generator. They also studied the effects of the pitch and twist ratio on the average heat transfer coefficient and the pressure loss. The results reveal that both heat transfer coefficient and friction factor in the dimpled tube fitted with the twisted tape, are higher than those in the dimple tube acting alone and plain tube. It is also found that the heat transfer coefficient and friction factor in the combined devices increase as the pitch ratio and twist ratio decrease.

Murugesan et al. [31] introduced the nails to the surface as shown in the Table 1. The tape's surface roughness was increased heavily, which lead additional turbulence offered by the wire nails besides the common swirling flow generated by the plain twisted tapes (P-TT). This spurs the Nusselt number, friction factor and thermal enhancement factor in the tube with twisted tape consisting wire nails (WN-TT) are respectively 1.08 to 1.31, 1.1 to 1.75 and 1.05 to 1.13 times of those in tube with plain twisted tapes (P-TT).

Saha [33] studied the twisted-tape inserts with and without oblique teeth. The axial corrugations in combination with twisted-tapes of all types with oblique teeth have been found performing better than those without oblique teeth in combination with axial corrugations.

3.3. Numerical work

Numerical simulation is another method to study the enhancement of heat transfer of various twist tapes in laminar and turbulent flow both for water and air. Eiamsa-ard et al. [34] developed a 3-D numerical model to study the swirling flow and convective heat transfer in a tube induced by loose-fit twisted tape insertion. The results show that the twisted tape inserts for $y=2.5$ with CR (clearance ratio)=0.0 (tight-fit), 0.1, 0.2 and 0.3 can enhance heat transfer rates up to 73.6%, 46.6%, 17.5% and 20%. The heat transfer augmentation is expected to involve the swirl flow formation between the tape and a tube wall. Chiu and Jang [35] investigated the thermal–hydraulic characteristics of air flow inside a circular tube with different tube inserts by 3-D numerical model verified by experimental testing. Three kinds of tube inserts were studied including the longitudinal strip inserts with and without holes, and twisted-tape inserts with three different twisted angles. The heat transfer and fluid flow performance were analysed by a 3D turbulence model with the consideration of conjugate convective heat transfer in the flow field and heat conduction in the tube inserts.

Guo et al. [36] studied the heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with centre-cleared twisted tape. The researchers demonstrated that the flow resistance can be reduced by narrow-width and center-cleared twisted tapes, however, the thermal behaviours are very different from each other. For tubes with narrow-width twisted tapes, the heat transfer and thermohydraulic performance are weakened by cutting off the tape edge. Contrarily, for tubes with center-cleared twisted tapes, the heat transfer can be even enhanced in the cases with a suitable central clearance ratio. All these indicated that the center-cleared twisted tape is a promising technique for laminar convective heat transfer enhancement. Furthermore, Shabanian [37] built up a CFD model to predict and explain the turbulence intensity and heat transfer enhancement in an air cooler equipped with different tubes inserts. The results illustrate that the predicted turbulence intensity of butterfly insert is higher than the jagged insert in the whole tube area. This can be the reason that more heat transfer rate is obtained by the butterfly insert compared to the jagged insert.

4. Coiled wire

The helical inserts are new addition to the family of inserts for enhancement of heat transfer. For the helical taps, the swirl moves in one direction along the helical and induce swirl in the flow, which increase the retention time of the flow and consequently provide better heat transfer performance over twisted tape insets. The high heat transfer with helical inserts is also accompanied by a higher pressure drop across the flow, but at low Reynolds number, helical tapes are used in solar water heating applications to drive heat transfer benefit. However inserts of different configuration are being used to meet the needs of higher heat dissipation rates. Wire coil inserts are currently used in the applications such as oil cooling devices, pre heaters or fire boilers. They show several advantages in relation to other enhancement techniques:

- Simple manufacturing process with low cost.
- Easy installation and removal.
- Preservation of original plain tube mechanical strength.
- Possibility of installation in an existing smooth tube heat exchanger.
- Fouling mitigation (in refineries, chemical industries and marine application).

4.1. Experimental work

The impacts of coiled wire on heat transfer enhancement inside tube and pipe heat exchanger are studied by García et al. [38] and Yakut and Sahin [39]. The vortex characteristics of tabulators, heat transfer rate and friction characteristics were considered as the criterions to evaluate the enhancement performance of coiled wire. García et al. experimentally studied the helical-wire-coils fitted inside a round tube in order to characterize their thermohydraulic behaviour in laminar, transition and turbulent flows. Results have shown that

- In laminar flow, wire coils behave as a smooth tube but accelerate transition to critical Reynolds numbers down to 700.
- At the low Reynolds numbers about $Re\approx 700$, transition from laminar to turbulent flow occurs in a gradual way.
- Within the transition region, heat transfer rate can be increased up to 200% when keep the pumping power constant.
- Wire coils have a predictable behaviour within the transition region since they show continuous curves of friction factor and Nusselt number, which involves a considerable advantage over other enhancement techniques.
- In turbulent flow, wire coils cause a high pressure drop which depends mainly on the pitch to wire-diameter ratio (p/e).
- In turbulent flow, the pressure drop and heat transfer are both increased by e up to nine times and four times respectively, compared to the empty smooth tube.

Therefore, it can be concluded that the wire coils do not cause obvious pressure drop and heat transfer rate increase, but induces the flow transition at a critical low Reynolds numbers at about 700. For pure turbulent flow, it can be stated that Prandtl number does not exert an influence on heat transfer augmentation. On the contrary, when working with high Prandtl number fluids within the transition region, wire coils produce the highest heat transfer

increase. Meanwhile, the wired coils offer their best performance within the transition region where they present a considerable advantage over other enhancement techniques.

Following the pervious researches, Promvonge et al. [40–43], experimentally studied the effects of wires coils with different square cross sections; coiled wires in conjunction with a snail-type swirl generator mounted at the tube entrance; wire coils in conjunction with twisted tapes used as a turbulator; and combined devices of the twisted tape (TT) and constant/periodically varying wire coil pitch ratio.

For the wires with square cross section, the Nusselt number augmentation tends to decrease rapidly with the rise of Reynolds number [40]. If wire coils are compared with a smooth tube at a constant pumping power, an increase in heat transfer is obtained, especially at low Reynolds number. Although fairly large differences have been observed among the analyzed coil wires, their evaluated performances are quite similar under the condition of $Re=5000$, heat transfer enhancement efficiency $(\eta)\approx 1.2$–1.3 and $Re=25{,}000$, $\eta \approx 1.1$–1.15. Therefore, the coiled square wire should be applied to obtain a higher thermohydraulic performance, but it will lead more compact heat exchanger construction.

The use of the coiled wires in conjunction with a snail-type swirls generator results in a high increase of the pressure drop but provides considerable heat transfer augmentations. The heat transfer enhancement ratio is from 3.4 to 3.9, and the Nusselt number augmentation tends to decrease with the rise of Reynolds number [41].

The best operating regime for combined turbulators is at lower Reynolds number and the lowest values of the coil spring pitch and twist ratio. Similar with the coiled wires used in reference [42], the Nusselt number augmentation tends to decrease with the rise of Reynolds number. Comparing the combined turbulators consisted of wire coil and twisted tape with a smooth tube at a constant pumping power, a double increase in heat transfer performance is obtained especially at low Reynolds number.

Then Promvonge et al. [43], investigated the combined devices consisted of the twisted tape (TT) and constant/periodically varying pitch ratio of the wire coil. They found that, at low Reynolds number, the device combined with TT at twist ratio of 3.0 and the DI-coil, provided the highest thermal performance which was around 6.3%, 13.7%, 2.4% and 3.7% higher than the wire coil alone, the TT alone, the TT with uniform wire coil, and the TT with D-coil, respectively.

Except the Promvonge's group, another two groups Gunes et al. [44] and Akhavan-Behabadi et al. [45], also investigated the thermohydraulic behaviour of coiled wires in tube and pipe heat exchangers in 2010. Gunes et al. experimentally investigated the coiled wire inserted in a tube for a turbulent flow regime. The coiled wire has equilateral triangular cross section and was inserted separately from the tube wall. They discovered that the Nusselt number rises with the increase of Reynolds number and wire thickness, and the decrease of pitch ratio; the best operating regime of all coiled wire inserts is detected at low Reynolds number, which leads to more compact heat exchanger; the pitch increases, the vortex shedding frequencies decrease and the maximum amplitudes of pressure fluctuation of vortices produced by coiled wire turbulators occur with small pitches.

Meanwhile, Akhavan-Behabadi et al. [45] investigated seven coiled wires with pitches from 12 mm to 69 mm, and wire diameters of 2.0 mm and 3.5 mm. These coiled wires are inserts inside a horizontal tube for heating the engine oil. The results show that the rise in fanning friction factor f due to the 2.0 mm thickness of the coiled wire insert for the Reynolds numbers less than 500. For Reynolds numbers higher than 500, the reduction in coil pitch causes an increase of the fanning friction factor.

4.2. Numerical work

Muñoz-Esparza and Sanmiguel-Rojas [46] employing the CFD simulation package investigated the heat transfer and fluid flow performance inside a round pipe with the helical wire coils inserts. They found that the friction factor becomes constant in the Re range of 600–850. The effect of the pitch on the friction factor has been addressed by performing a parametrical study with a pitch-periodic computational domain for wire coils within the dimensionless pitch range (p/d), $1.50 \le p/d \le 4.50$, and dimensionless wire diameter, $e/d=0.074$, showing that the increase of p/d, decreases the friction factor.

Solanoa et al. [47] used CFD to study the effect of helical wire on the enhancement of heat transfer in pipe subjected to uniform heat flux and laminar the flow. The results show that during the deceleration period of both oscillating semicycles, laminar eddies grow downstream of the wire and spread along the next helical pitch, promote radial mixing.

5. Swirl generators

Swirl flows have wide range of applications in various engineering areas such as chemical and mechanical mixing and separation devices, combustion chambers, turbo machinery, rocketry, fusion reactors, pollution control devices, etc. The utilization of swirl flows may lead to the heat and mass transfer enhancements. Problems of heat and mass transfer in swirl pipe flows are the practical importance in designing different heat exchangers, submerged burners, heat transfer promoters and chemical reactors.

Swirl flows result from an application of a spiral motion, a swirl velocity component (also called as 'tangential' or 'azimuthal' velocity component) being imparted to the flow by the use of various swirl-generating methods. Many researchers have studied the heat transfer characteristics of swirl flows by using various swirls. Generally, the swirling pipe flows are classified into two types: (i) Continuous swirl flows, which maintain their characteristics over entire length of test section; and (ii) decaying swirl flows. Additional difference in properties of swirl flows is related with the rate of swirl intensity.

This traditional classification of swirl flows is not sufficient for explanation of the heat and mass transfer in swirl flows. From the hydrodynamic point of view, the major problem is an incomplete understanding of the swirl flow parameters. Swirl flow is usually referred to a vortex structure with a central vortex core and an axial velocity component. Recent progress in study of these vortex structures reveals the direct relation between the type of vortex symmetry (left- or right-handed symmetry) and the appearance of swirl flows with jet-like or wake-like. In radial guide vane swirl generators, the flow direction changes from the radial direction to the axial direction

5.1. Experimental work

Yilmaz et al. [48] studied the effect of the geometry of the deflecting element in the radial guide vane swirl generator on the heat transfer and fluid friction characteristics in decaying swirl flow. The results show that an augmentation up to 150% in Nusselt number relative to that of the fully developed axial flow was obtained with a constant heat flux boundary condition. The exact segmentation depends upon the vane angles, Reynolds numbers and types of the swirl generators. They observed that the swirl generator with no deflecting element presented the highest Nusselt numbers and also the highest pressure drop in both the swirl generator and the tested pipe; the swirl generator

with no deflecting element may be advantageous in terms of heat transfer enhancement and energy saving in comparison with swirl generators with a deflecting element; in swirling flow, increasing the Reynolds number and the vane angle increased the Nusselt number; to obtain lower pumping powers for the same heat transfer rate, higher vane angles and relatively lower Reynolds numbers must be employed.

A vortex generator with propeller-type geometry to produce swirl flow in a horizontal pipe was investigated by Saraç and Bali in 2007 [49]. The heat transfer and pressure drop characteristics of decaying swirl flow through a circular pipe with a vortex generator were studied. They discovered that the Nusselt numbers increased from 18.1% to 163% which depends on the Reynolds number, the position of the vortex generator, the angle and the number of the vanes; with the decaying of the swirl flow, the heat transfer and pressure drop decreased gradually away from the axial; the inserts with six vanes resulted in more heat transfer values than those with four vanes.

Kurtbaş et al. [50] devised a novel conical injector type swirl generator (CITSG) and experimentally examined the performances of heat transfer and pressure drop in a pipe with the CITSG. Moreover, circular holes with different numbers (N) of conical and cross-section areas (A_h) are drilled on the CITSG. They found that the Nu decreases with the increase of Reynolds number, the director angle (β), the director diameter (d), and with the decrease of the CITSG angle (α); the effect of the β on Nu_x is at negligible level for higher Re.

Eiamsa-ard et al. [51] studying the heat transfer, friction loss and enhancement efficiency behaviours in a heat exchanger tube equipped with propeller type swirl generators at several pitch ratios. The swirl generator is used to create a decaying swirl in the tube flow. The results indicate that the use of the propeller leads to maximum enhancement efficiency up to 1.2. Thus, because of strong swirl or rotating flow, the propellers and their blade numbers become influential upon the heat transfer enhancement. The increase in friction factor from using the propeller is found to be 3–18 times over the plain tube. The heat transfer and the enhancement efficiency are found to increase with increasing the blade number (N) and the blade angle (θ) but to decrease with the rise of pitch ratio. Depending on Reynolds numbers, the increases in heat transfer rate are about 113%, 90%, and 73% above the plain tube, for PR=5.0, 7.0, and 10.0, respectively.

Yang et al. [52] studied the heat transfer process of swirling flow issued into a heated convergent pipe with a convergent angle of 5° with respect to the pipe axis as shown in the Tables 5–10. A flat vane swirler situated at the entrance of the pipe is used to generate the swirling flow. The results show that the convergence of the pipe can accelerate the flow which has an effect to suppress the turbulence generated in the flow and reduce the heat transfer. However, in the region of weak swirl (S=0–0.65), the Nusselt numbers increase with the increase of swirl numbers until S=0.65, where the turbulence intensity is expected to be large enough and not suppressible. In the region of strong swirl ($S>0.65$), where recirculation flow is expected to be generated in the core of the swirling flow, the heat transfer characteristic can be altered significantly. At very high swirl value ($S\geq 1.0$), the accelerated flow in the circumferential direction is expected to be dominant, which leads to suppress the turbulence and reduce the heat transfer.

5.2. Numerical work

Martemianov and Okulov [53], developed a theoretical model of the heat transfer in the axisymmetric swirl pipe flows. The influences of vortex symmetry and vorticity distribution at the vortex core on the heat transfer enhancement were studied. The study shows that there are two types of vortex structures existing in the swirl flows with the same integral characteristics: vortices with left-handed helical symmetry and vortices with right-handed helical symmetry. The left-handed helical vortexes generate wake-like swirl flows and increase the heat transfer in comparison with the axial flow. Right-handed vortex structures generate jet-like swirl flows and can diminish heat transfer. The authors concluded that there are two major factors influencing the heat transfer enhancement: formation of the swirl flow with left hand helical vortex and modification of the near wall velocity profile of the inviscid flow due to the different vorticity distribution in the vortex core.

6. Conical ring

Promvonge [54–61] studied different type of shapes and configuration of conical ring, conical ring integrated with twisted tape, conical-nozzles combined with swirl generator, free-spacing snail entry together with conical-nozzle turbulators, converging nozzle with different pitch ratios (PR), diverging nozzle arrangement, converging nozzle arrangement, V-nozzle turbulators, diamond-shaped turbulators in tandem arrangements. In 2006, Promvonge's research group found that the heat transfer in the circular tube is enhanced by the conical-nozzles combined with swirl generator, but induced higher energy loss of the fluid flow,

Table 5
Configuration sketches of various swirl generators.

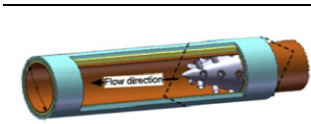
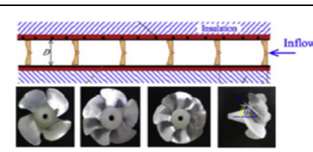
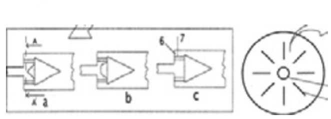
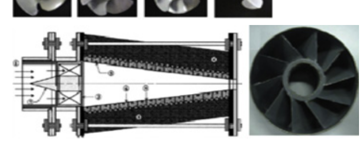
Configuration	Name	Reference	Configuration	Name	Reference
	Conical injector	[50]		Propeller swirl generators	[51]
	Radial guide vane swirl generators	[48]		Typical swirler	[52]
	Propeller swirl generator	[49]			

Table 6
Experimental works on the thermohydraulic performance of swirl generators enhancement.

Authors	Working fluid	Configuration	Conditions	Observation
Yilmaz et al. [48]	Air	• The swirl generator with conical deflecting element, • The swirl generator with spherical deflecting element	• $32000 \leq Re \leq 111000$	• The swirl generator with no deflecting element may be advantageous in terms of heat transfer enhancement and energy saving in comparison with swirl generators with a deflecting element • In swirling flow, increasing the Reynolds number and the vane angle increased the Nusselt number • To obtain lower pumping powers for the same heat transfer rate, higher vane angles and relatively lower Reynolds numbers must be employed
Saraç and Bali [49]	Air	• Propeller-type geometry	• $5000 \leq Re \leq 30000$ • Positions of the vortex generator in the axial direction are examined: at the inlet $x=0$, $x=L/4$ and $x=L/2$.	• For the decaying swirl flow, the heat transfer and pressure drop decreased with the axial distance • The inserts with six vanes resulted in more heat transfer values than those with four vanes • For the decaying swirl flow, the heat transfer and pressure drop decreased with the axial distance • The inserts with six vanes resulted in more heat transfer values than those with four vanes
kurtbs et al. [50]	Air	• Conical injector type swirl generator (CITSG)	• $9400 \leq Re \leq 35000$ • CITSGs' angle (α) of 30°, 45° and 60°	• The heat transfer ratio (Nu_{PR}) decreases with increase in Re • The effect of the α on Nu_x is at negligible level for higher Re • The heat transfer enhancement ratio (Nu_{ER}) decreases with the increase in Re and increases with the β and DR increase
Eiamsa-ard et al. [51]	Air	• Propeller type swirl generators at several pitch ratios (PR)	• $4000 \leq Re \leq 21000$ • Blade numbers of the propeller ($N=4$, 6 and 8 blades) • Different blade angles ($\theta=30°$, 45°, and 60°)	• The heat transfer in the test tube can be enhanced considerably by insertion of the propeller type swirl generators. The heat transfer and the enhancement efficiency are found to increase with increasing the blade number (N) and the blade angle (θ) but to decrease with the rise of pitch ratio (PR)
Yang et al. [52]	Air	• Flat vane swirler situated at the entrance of the pipe	• $7970 \leq Re \leq 47820$	• The Nusselt number is found to increase monotonically with both the Reynolds and the swirl numbers in the weak swirling flow region • the Nusselt number decreases with increasing the swirl numbers due to suppression effect of accelerated circumferential flow

Table 7
Configuration sketches of various swirl concial ring.

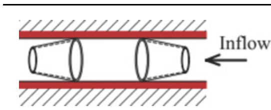
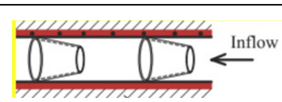
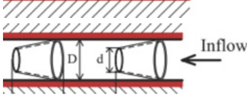
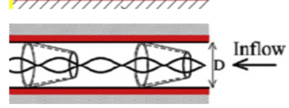
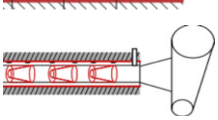
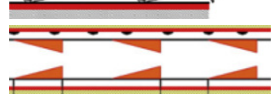
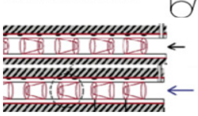
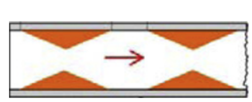
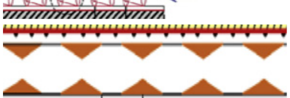
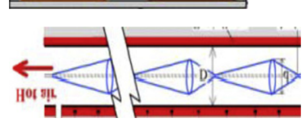
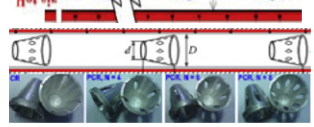
Configuration	Name	Reference	Configuration	Name	Reference
	Converging diverging conical ring	[54]		Diverging conical ring	[54]
	Converging conical ring	[54]		Conical-ring with twisted tape	[55]
	Conical nozzles combined with a snail	[56]		Conical-nozzle	[57]
	Coilcial-nozzle tabulator	[58]		V- nozzle turbulator	[59]
	V-nozzle turbulator	[60]		Tandem diamond-shaped tabulator	[61]
	Conical tube insert	[62]		Perforated conical-rings	[63]

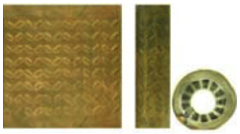
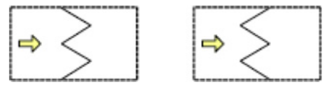
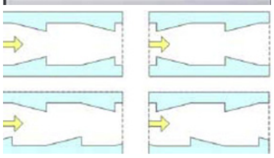
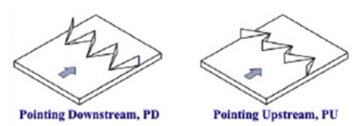
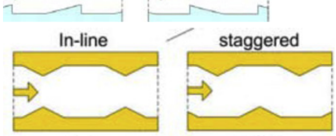
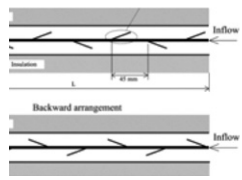
Table 8
Experimental works on the thermohydraulic performance of conical rings enhancement.

Authors	Working fluid	Configuration	Conditions	Observation
Promvonge [54]	Air	• Conical rings arrangements	• $6000 \le Re \le 26000$	• Although the effect of using the conical ring causes a substantial increase in friction factor
Promvonge and Eiamsa-ard [55]	Air	• Conical-ring turbulators and a twisted-tape swirl generator	• $6000 \le Re \le 26000$ • Twisted-tapes twist ratios $y=3.75$ and 7.5	• For all the devices used, the enhancement efficiency tends to decrease with the rise of Reynolds number and to be nearly uniform for Reynolds number over 16,000 • the smaller twist ratio is, the larger the heat transfer and friction factor for all Reynolds numbers
Promvonge and Eiamsa-ard [56]	Air	• Conical nozzles and swirl generator	• $8000 \le Re \le 18000$ • Ratios (PR) of conical-nozzle arrangements PR=2.0, 4.0 and 7.0 • Uniform heat flux	• The heat transfer in the circular tube could be enhanced considerably by fitting it with conical-nozzle inserts and snail entrance. Although they provide higher energy loss of the fluid flow; the loss is low especially at low Reynolds number • The turbulators are applicable effectively at low Reynolds number because they provide low enhancement efficiency at high Reynolds number for all PRs
Promvonge and Eiamsa-ard [57]	Air	• Conical-nozzle turbulators	• $8000 \le Re \le 18000$ • Uniform heat-flux tube • Conical or converging nozzle (C-nozzle) • PR=2.0, 4.0 and 7.0	• C-nozzle turbulators and a snail with free-spacing entry can be employed effectively at low Reynolds number or in places where pumping power is not important but compact sizes and ease of manufacture are needed
Promvonge and Eiamsa-ard [58]	Air	• Conical-nozzle turbulator	• $8000 \le Re \le 18000$ • PR=2.0, 4.0, and 7.0 • Diverging nozzle arrangement (D-nozzle) • Converging nozzle arrangement (C-nozzle)	• The heat transfer rate in the test tube can be promoted by fitting with nozzle-turbulators. Despite very high friction, the turbulators can be applied effectively in places where pumping power is not significantly taken into account but the compact size including ease of manufacture installation is required
Promvonge and Eiamsa-ard [59]	Air	• V-nozzle turbulator inserts in conjunction with a snail entry	• $8000 \le Re \le 18000$ • PR=2.0, 4.0, and 7.0	• V-nozzle alone provides the best thermal performance over other turbulator devices
Eiamsa-ard and Promvonge [60]	Air	• V-nozzle turbulator inserts	• $8000 \le Re \le 18000$ • PR=2.0, 4.0, and 7.0	• The enhancement efficiency decreases with increasing Reynolds number
Eiamsa-ard and Promvonge [61]	Air	• Tandem diamond-shaped turbulators (D-shape turbulator)	• $3500 \le Re \le 16500$ • Cone angle ($\theta=15^\circ$, 30° and 45°) • Tail length ratio ($TR=l_t/l_h=1.0$, 1.5 and 2.0)	• The increase in the heat transfer rate with increasing the cone angle and decreasing the tail length ratio is due to the higher turbulence intensity imparted to the flow between the turbulators and the heating wall. Since the turbulators are placed directly into the flow core, they cause high friction losses because of high flow blockage
Anvari et al. [62]	Water	• Conical tube inserts	• $2500 \le Re \le 9500$	• The insertion of turbulators has significant effect on the enhancement of heat transfer, especially the DR arrangement, and also they increase the pressure drop. So turbulators can be used in places where the compact size is more significant than pumping power
Kongkaitpaiboon et al. [63]	Air	• Perforated conical-ring (PCR)	• $4000 \le Re \le 20000$ • Pitch ratios ($PR=p/D=4$, 6 and 12) • Perforated holes ($N=4$, 6 and 8 holes)	• The heat transfer rate and friction factor of PCRs increase with decreasing pitch ratio (PR) and decreasing number of perforated hole (N). However, the thermal performance factor increases with increasing number of perforated hole and decreasing pitch ratio

which can be reduced at low Reynolds number. Therefore the applications of this kind of turbulators are more effectively at low Reynolds number rather than high Reynolds number. The same year, this group also investigated the impact of V-nozzle turbulators on heat transfer. The enhancement efficiency decreases by increasing the Reynolds number. The maximum enhancement efficiency obtained by using the V-nozzle with a PR value of 2.0, 4.0, and 7.0, are found to be 1.19, 1.14, and 1.09, respectively.

The enhancement efficiency increases as the pitch decreases and it generally will be lower at high Reynolds number for all pitches. Four more similar researches were carried out by Promvonge et al. in 2007, they found these: (i) Inserts combined conical-ring and twisted-tape the enhancement efficiency tends to decrease with the rise of Reynolds number and to be nearly uniform for Reynolds number over 16,000. The larger the heat transfer and friction factor for all Reynolds numbers can be

Table 9
Configuration sketches of insert ribs.

Configuration	Name	Reference	Configuration	Name	Reference
	Inclined ribs	[66]		Discrete double-inclined ribs	[64]
	Helical rib	[65]		Combined rib with rectangular Winglet	[68]
	Combined wedge ribs and winglet type vortex	[69]		Combined rib with delta-winglet	[70]
	Triangular rib	[71]		Louvered strip	[67]

achieved at a smaller twist ratio; (ii) C-nozzle turbulators and a snail with free-spacing entry can be employed effectively at low Reynolds number or in places where pumping power are not important but compact sizes and ease manufacture process are needed; (iii) Despite very high friction, the conical-nozzle turbulators can be applied effectively in places where pumping power is not significantly taken into account but the compact size, ease of manufacture and installation are required; (iv) V-nozzle alone provides the best thermal performance over other nozzle turbulator devices.

In 2008, Promvonge et al. confirmed again the substantial increase in friction factor. Therefore, a diamond-shaped element is introduced into the turbulent tube flows by Promvonge et al. in 2010. The heat transfer rate increase with the increasing of the cone angle and decreasing of the tail length ratio, which induces higher turbulence intensity imparted to the flow between the turbulators and the heating wall. Meanwhile, the turbulators are placed directly into the flow core causing high friction losses because of the high flow blockage.

Anvari et al. [62] studied the impact of conical ring inserts in transient regime. The insertion of turbulators has significant effect on the enhancement of heat transfer, especially the DR (Divergent rings) arrangement, and also increase the pressure drop. So tabulators can be used in places where the compact size is more significant than pumping power.

Kongkaitpaiboon et al. [63] studied experimentally the influences of the PCR (perforated conical-rings) on the turbulent convective heat transfer, friction factor, and thermal performance factor. It is found that the PCR considerably diminishes the development of thermal boundary layer, leading to the heat transfer rate up to about 137% over that in the plain tube. Evidently, the PCRs can enhance heat transfer more efficient than the typical CR on the basis of thermal performance factor of around 0.92 at the same pumping power.

7. Rib

Ribs are another technology enhancing the heat transfer rate. The heat transfer performances in discrete double-inclined ribs tube (DDIR-tube) were numerically and experimentally investigated by Meng et al. [64]. FLUENT 6.0 was used to solve the field synergy equation numerically. Numerical solution of the field synergy equation of laminar convection heat transfer in a straight circular tube together with other governing equations indicates that the multi-longitudinal vortex flow is the best way for heat transfer enhancement in laminar convection in tubes. The flow field of the DDIR-tube is similar to the optimal velocity field. The experimental results show that the DDIR-tube has better comprehensive heat transfer performance than the current heat transfer enhancement tubes. The present work indicates that new heat transfer enhancement techniques could be developed according to the optimum velocity field. Therefore the comprehensive performances of enhanced laminar heat transfer in DDIR-tube are better than that of the currently-known enhancement techniques.

Naphon et al. [65] experimentally studied the heat transfer and pressure drop characteristics in horizontal double pipes with helical ribs. Nine test sections with different characteristic parameters of: helical rib height to diameter, $v/d=0.12$, 0.15, 0.19, and helical rib pitch to diameter, $p/d=1.05$, 0.78, 0.63 are tested. The results show that the helical ribs have a significant effect on the heat transfer and pressure drop augmentations. The pressure drop across the tube with helical rib is produced by: (i) drag forces exerted on the flow field by the helical rib, (ii) flow blockage due to area reduction, (iii) turbulence augmentation and (iv) rotational flow produced by the helical rib.

Li et al. [66] experimentally and numerically studied the turbulent heat transfer and flow resistance in an enhanced heat transfer in Discrete Double Incline Ribs (DDIR) tube. The results show that the heat transfer in the DDIR tube is enhanced from 100 to 120% contrasted with a plain tube and the pressure drop is increased from 170% to 250%. The heat transfer rate at the same pumping power is enhanced by 30 to 50%. The numerical simulations solved the three dimensional Reynolds-averaged Navier–Stokes equations with the standard k–e model in the commercial CFD code, Fluent. The numerical results agree well with the experimental data, with the largest discrepancy of 10% for the Nusselt numbers and 15% for the friction factors. Visualization of the flow field shows that in addition to the front and rear vortices around the ribs, main vortices and induced vortices

Table 10
Experimental works on the thermohydraulic performance of insert ribs enhancement.

Authors	Working fluid	Configuration	Conditions	Observation
Naphon et al. [65]	Water	• Horizontal double pipes with helical ribs	• $15000 \le Re \le 60000$	• Helical ribs have a significant effect on the heat transfer and pressure drop augmentations
Li et al. [66]	Water	• Discrete double inclined ribs	• $15000 \le Re \le 60000$	• Visualization of the flow field shows that in addition to the front and rear vortices around the ribs, main vortices and induced vortices are also generated by the ribs in the DDIR tube. The rear vortex and the main vortex contribute much to the heat transfer enhancement in the DDIR tubes
Eiamsa et al. [67]	Water	• Louvered strip	• $6000 \le Re \le 42000$ • Forward or backward arrangements • Inclined angles (θ=15°, 25° and 30°)	• Louvered strip insertions can be used efficiently to augment heat transfer rate because the turbulence intensity • The highest heat transfer rate was achieved for the backward inclined angle of 30° due to the increase of strong turbulence intensity
Depaiwa et al. [68]	Air	• Rectangular winglet vortex generator (WVG)	• $5000 \le Re \le 23000$ • Attack angles (α) of 60°, 45° and 30° • DW=b/H=0.4 • Transverse pitch, P_t/H=1	• Solar air heater channel with rectangular WVG provides significantly higher heat transfer rate and friction loss than the smooth wall channel
Chompookham et al. [69]	Air	• Combined wedge ribs and winglet type vortex generators (WVGs)	• $5000 \le Re \le 22000$ • Uniform heat-flux tube • Attack angle 60° • Rib height, e/H=0.2 • Rib pitch, P/H=1.33	• The combination of staggered wedge rib and the WVGs has efficiently performed and should be applied to obtain higher thermal performance at about 17–20% of a single use of turbulators
Promvonge et al. [70]	Air	• Combined ribs and delta-winglet type vortex generators (DWs)	• $5000 \le Re \le 22000$ • Attack angles (α) of 60°, 45° and 30°	• The *Nu* decrease slightly with the rise in *Re* • Combined rib and PD-DW at lower angle of attack provides higher heat transfer • The best operating regime for using these compound turbulators is found at the PD-DW arrangement, lower attack angle and/or *Re* values
Promvonge et al. [71]	Air	• Combined wedge ribs and winglet type vortex generators (WVGs)	• $5000 \le Re \le 22000$. • Attack angle 30°, 45°, 60°	• The Nusselt number augmentation tends to decrease slightly with the rise in Reynolds number • The best operating regime for using these compound turbulators is found at the lower attack angle and/or Reynolds number values

are also generated by the ribs in the DDIR tube. The rear vortex and the main vortex contribute much to the heat transfer enhancement in the DDIR tubes.

Eiamsa-ard et al. [67], investigated the louvered strips inserted in a concentric tube heat exchanger in 2008. The louvered strip was inserted into the tube to generate turbulent flow which helped to increase the heat transfer rate of the tube. Experimental results confirmed that the use of louvered strips leads to a higher heat transfer rate over the plain tube. The use of the louvered strip with backward arrangement leads to better overall enhancement ratio than that with forward arrangement around 9% to 24%.

Depaiwa et al. [68] experimentally studied the turbulent airflow through channel solar air heater with rectangular winglet vortex generator (WVG). The results present that the solar air heater channel with rectangular WVG provides significantly higher heat transfer rate and friction loss than the smooth wall channel. The use of larger attack angle value leads to higher heat transfer rate and friction loss than that of lower one. Chompookham et al. [69] experimentally investigated the effect of combined wedge ribs and winglet type vortex generators (WVGs) in 2010. They used two types of wedge (right-triangle) ribs pointing downstream and upstream to create a reverse flow in the channel. The arrangements of both rib types placed inside the opposite channel walls are in-line and staggered arrays. The results show that the combined ribs and the WVGs show the significant increase in heat transfer rate and friction loss over the smooth channel.

Two more projects were published by Promvonge et al. [70,71]. They experimentally studied the effects of combined ribs with delta-winglet type vortex generators (DWs) and integrated ribs with winglet type vortex generators (WVGs) on forced convection heat transfer and friction loss behaviours for turbulent airflow through a solar air heater channel. Results show that the Nusselt number and friction factor values for combined rib with DW are much higher than those for the rib/DW alone and have significant effect of the presence of the rib turbulator and the WVGs on the heat transfer rate and friction loss over the smooth wall channel. The values of Nusselt number and friction factor for utilizing both the rib and the WVGs are found to be considerably higher than those for using the rib or the WVGs alone.

8. Conclusions

(i) Full length twisted tape (FLTT) increases the pressure drop comparing to an empty tube. The pressure drop depends on the tape geometry and is always larger than185% for any FLTT geometry.

(ii) Most of the researches need to reduce the extra pressure drop by using short length twisted tape (SLTT) located at the inlet of channel or multiple short length twisted tapes (MSLTTs) inserted into a long channel and spaced by an empty length.
(iii) MSLTTs yield a lower pressure drop than a FLTT at the same twisted ratio.
(iv) Twisted tape inserts perform better in laminar flow.
(v) Twisted tape in turbulent flow insert is not very effective.
(vi) If the pressure drop is not concerned, twisted tape inserts are preferred in both laminar and turbulent regions.
(vii) Helical screw tape can help to promote higher heat transfer exchange rate than the use of twisted-tape because of that shorter pitch length leads to stronger swirling flow and longer residence time in the tube.
(viii) In the selection of the tube inserts, the shape of the insert is important.
(ix) Wire coil gives better overall performance if the pressure drop penalty is considered.
(x) The other several passive techniques to enhance the heat transfer in a flow, such as ribs, conical nozzle, are generally more efficient in the turbulent flow than in the laminar flow.

References

[1] Elshafei EAM, Safwat Mohamed M, Mansour H, Sakr M. Experimental study of heat transfer in pulsating turbulent flow in a pipe. International Journal of Heat and Fluid Flow 2008;29:1029–38.
[2] Liebenberg L, Meyer JP. In-tube passive heat transfer enhancement in the process industry. Applied Thermal Engineering 2007;27:2713–26.
[3] Alamgholilou A, Esmaeilzadeh E. Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular ribs by passive and EHD active enhancement methods. Experimental Thermal and Fluid Science 2012;38:61–73.
[4] Dewan A, Mahanta P, Sumithra K, Suresh P. Review of passive heat transfer augmentation techniques. Part A: Journal of Power and Energy 2004:509–27.
[5] Kumar A, Prasad BN. Investigation of twisted tape inserted solar water heaters—heat transfer, friction factor and thermal performance results. Renewable Energy 2000;19:379–98.
[6] Noothong W, Eiamsa-ard S, Promvonge P. Effect of twisted-tape inserts on heat transfer in a tube. In: The 2nd joint international conference on "Sustainable Energy and Environment (SEE 2006). 21–23 November 2006, Bangkok, Thailand. 1–5.
[7] Sarada N, Raju S, Kalyani Radha AV, Shyam K. Enhancement of heat transfer using varying width twisted tape inserts'. International Journal of Engineering, Science and Technology 2010;2(6):107–18.
[8] Eiamsa-ard S, Thianpong C, Eiamsa-ard P, Promvonge P. Convective heat transfer in a circular tube with short-length twisted tape insert. International Communications in Heat and Mass Transfer 2009;36:365–71.
[9] Jaisankar S, Radhakrishnan TK, Sheeba KN, Suresh S. Experimental investigation of heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of left–right twisted tapes. Energy Conversion and Management 2009;50:2638–49.
[10] Eiamsa-ard S, Wongcharee K, Eiamsa-ard P, Thianpong C. Thermohydraulic investigation of turbulent flow through a round tube equipped with twisted tapes consisting of centre wings and alternate-axes. Experimental Thermal and Fluid Science 2010;34:1151–61.
[11] Wongcharee K, Eiamsa-ard S. Friction and heat transfer characteristics of laminar swirl flow through the round tubes inserted with alternate clockwise and counter-clockwise twisted-tapes. International Communications in Heat and Mass Transfer 2011;38:348–52.
[12] Eiamsa-ard S, Thianpong C, Eiamsa-ard P, Promvonge P. Thermal characteristics in a heat exchanger tube fitted with dual twisted tape elements in tandem. International Communications in Heat and Mass Transfer 2010;37:39–46.
[13] Eiamsa-ard S. Study on thermal and fluid flow characteristics in turbulent channel flows with multiple twisted tape vortex generators. International Communications in Heat and Mass Transfer 2010;37:644–51.
[14] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with spacer at the trailing edge of twisted tapes. Applied Thermal Engineering 2009;29:1224–31.
[15] Krishna SR, Pathipaka G, Sivashanmugam P. Heat transfer and pressure drop studies in a circular tube fitted with straight full twist. Experimental Thermal and Fluid Science 2009;33:431–8.
[16] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with left–right twisted tapes. International Energy Journal 2008;9:1–5.
[17] Jaisankar S, Radhakrishnan TK, Sheeba KN. Studies on heat transfer and friction factor characteristics of thermosyphon solar water heating system with helical twisted tapes. Energy 2009;34:1054–64.
[18] Jaisankar S, Radhakrishnan TK, Sheeba KN. Experimental studies on heat transfer and thermal performance characteristics of thermosyphon solar water heating system with helical and left–right twisted tapes. Energy Conversion and Management 2011;52:2048–55.
[19] Eiamsa-ard S, Wongcharee K, Eiamsa-ard P, Thianpong C. Heat transfer enhancement in a tube using delta-winglet twisted tape inserts. Applied Thermal Engineering 2010;30:310–8.
[20] Wongcharee K, Eiamsa-ard S. Heat transfer enhancement by twisted tapes with alternate-axes and triangular, rectangular and trapezoidal wings. Chemical Engineering and Processing: Process Intensification 2011;50:211–9.
[21] Murugesan P, Mayilsamy K, Suresh S, Srinivasan P. Heat transfer and pressure drop characteristics of turbulent flow in a tube fitted with trapezoidal-cut twisted tape insert. International Journal of Academic Research 2009;1:123–7.
[22] Seemawute P, Eiamsa-ard S. Thermohydraulics of turbulent flow through a round tube by a peripherally-cut twisted tape with an alternate axis. International Communications in Heat and Mass Transfer 2010;37:652–9.
[23] Eiamsa-ard S, Seemawute P, Wongcharee K. Influences of peripherally-cut twisted tape insert on heat transfer and thermal performance characteristics in laminar and turbulent tube flows. Experimental Thermal and Fluid Science 2010;34:711–9.
[24] Murugesan P, Mayilsamy K, Suresh S, Srinivasan PSS. Heat transfer and pressure drop characteristics in a circular tube fitted with and without V-cut twisted tape insert. International Communications in Heat and Mass Transfer 2011;38:329–34.
[25] Ibrahim EZ. Augmentation of laminar flow and heat transfer in flat tubes by means of helical screw-tape inserts. Energy Conversion and Management 2011;52:250–7.
[26] Moawed M. Heat transfer and friction factor inside elliptic tubes fitted with helical screw-tape inserts. Journal of Renewable Sustainable Energy 2011;3:1–15.
[27] Sivashanmugam P, Nagarajan PK. Studies on heat transfer and friction factor characteristics of laminar flow through a circular tube fitted with right and left helical screw-tape inserts. Experimental Thermal and Fluid Science 2007;32:192–7.
[28] Sivashanmugam P, Suresh S. Experimental studies on heat transfer and friction factor characteristics of laminar flow through a circular tube fitted with helical screw-tape inserts. Applied Thermal Engineering 2006;26:1990–7.
[29] Krishna SR, Pathipaka G, Sivashanmugam P. Studies on heat transfer augmentation in a circular tube fitted with straight half twist left–right inserts in laminar flow. Journal of Environmental Research And Development 2008;3:437–41.
[30] Eiamsa-ard S, Promvonge P. Thermal characteristics in round tube fitted with serrated twisted tape. Applied Thermal Engineering 2010;30:1673–82.
[31] Murugesan P, Mayilsamy K, Suresh S. Heat transfer and friction factor studies in a circular tube fitted with twisted tape consisting of wire-nails. Chinese Journal of Chemical Engineering 2010;18:1038–42.
[32] Thianpong C, Eiamsa-ard P, Wongcharee K, Eiamsa-ard S. Compound heat transfer enhancement of a dimpled tube with a twisted tape swirl generator. International Communications in Heat and Mass Transfer 2009;36:698–704.
[33] Saha SK. Thermohydraulics of turbulent flow through rectangular and square ducts with axial corrugation roughness and twisted-tapes with and without oblique teeth. Experimental Thermal and Fluid Science 2010;34:744–52.
[34] Eiamsa-ard S, Wongcharee K, Sripattanapipat S. 3-D Numerical simulation of swirling flow and convective heat transfer in a circular tube induced by means of loose-fit twisted tapes. International Communications in Heat and Mass Transfer 2009;36:947–55.
[35] Chiu Y, Jang J. 3D numerical and experimental analysis for thermal–hydraulic characteristics of air flow inside a circular tube with different tube inserts. Applied Thermal Engineering 2009;29:250–8.
[36] Guo J, Fan A, Zhang X, Liu W. A numerical study on heat transfer and friction factor characteristics of laminar flow in a circular tube fitted with center-cleared twisted tape. International Journal of Thermal Sciences 2011;50:1263–70.
[37] Shabanian SR, Rahimi M, Shahhosseini M, Alsairafi AA. CFD and experimental studies on heat transfer enhancement in an air cooler equipped with different tube inserts. International Communications in Heat and Mass Transfer 2011;38:383–90.
[38] García A, Vicente PG, Viedma A. Experimental study of heat transfer enhancement with wire coil inserts in laminar-transition-turbulent regimes at different Prandtl numbers, Int. Journal of Heat and Mass Transfer 2005;48:4640–51.
[39] Yakut K, Sahin B. The effects of vortex characteristics on performance of coiled wire turbulators used for heat transfer augmentation. Applied Thermal Engineering 2004;24:2427–38.
[40] Promvonge P. Thermal performance in circular tube fitted with coiled square wires. Energy Conversion and Management 2008;49:980–7.
[41] Promvonge P. Thermal enhancement in a round tube with snail entry and coiled-wire inserts. International Communications in Heat and Mass Transfer 2008;35:623–9.

[42] Promvonge P. Thermal augmentation in circular tube with twisted tape and wire coil turbulators. Energy Conversion and Management 2008;49:2949–55.
[43] Eiamsa-ard S, Nivesrangsan P, Chokphoemphun S, Promvonge P. Influence of combined non-uniform wire coil and twisted tape inserts on thermal performance characteristics. International Communications in Heat and Mass Transfer 2010;37:850–6.
[44] Gunes S, Ozceyhan V, Buyukalaca O. Heat transfer enhancement in a tube with equilateral triangle cross sectioned coiled wire inserts. Experimental Thermal and Fluid Science 2010;34:684–91.
[45] Akhavan-Behabadi MA, Kumar R, Salimpour MR, Azimi R. Pressure drop and heat transfer augmentation due to coiled wire inserts during laminar flow of oil inside a horizontal tube. International Journal of Thermal Sciences 2010;49:373–9.
[46] Muñoz-Esparza D, Sanmiguel-Rojas E. Numerical simulations of the laminar flow in pipes with wire coil inserts. Computers & Fluids 2011;44:169–77.
[47] Solano JP, Herrero R, Espín S, Phan AN, Harvey AP. Numerical study of the flow pattern and heat transfer enhancement in oscillatory baffled reactors with helical coil inserts. Chemical Engineering Research and Design 2012;90:732–42.
[48] Yilmaz M, Comakli O, Yapici S, Sara ON. Heat transfer and friction characteristics in decaying swirl flow generated by different radial guide vane swirl generators. Energy Conversion and Management 2003;44:283–300.
[49] Saraç BA, Bali T. An experimental study on heat transfer and pressure drop characteristics of decaying swirl flow through a circular pipe with a vortex generator. Experimental Thermal and Fluid Science 2007;32:158–65.
[50] Kurtbaş İ, Gülçimen F, Akbulut A, Buran D. Heat transfer augmentation by swirl generators inserted into a tube with constant heat flux. International Communications in Heat and Mass Transfer 2009;36:865–71.
[51] Eiamsa-ard S, Rattanawong S, Promvonge P. Turbulent convection in round tube equipped with propeller type swirl generators. International Communications in Heat and Mass Transfer 2009;36:357–64.
[52] Yang CS, Jeng DZ, Yang Y, Chen H, Gau C. Experimental study of pre-swirl flow effect on the heat transfer process in the entry region of a convergent pipe. Experimental Thermal and Fluid Science 2011;35:73–81.
[53] Martemianov S, Okulov VL. On heat transfer enhancement in swirl pipe flows. International Journal of Heat and Mass Transfer 2004;47:2379–93.
[54] Promvonge P. Heat transfer behaviors in round tube with conical ring inserts. Energy Conversion and Management 2008;49:8–15.
[55] Promvonge P, Eiamsa-ard S. Heat transfer behaviors in a tube with combined conical-ring and twisted-tape insert. International Communications in Heat and Mass Transfer 2007;34:849–59.
[56] Promvonge P, Eiamsa-ard S. Heat transfer enhancement in a tube with combined conical-nozzle inserts and swirl generator. Energy Conversion and Management 2006;47:2867–82.
[57] Promvonge P, Eiamsa-ard S. Heat transfer in a circular tube fitted with free-spacing snail entry and conical-nozzle turbulators. International Communications in Heat and Mass Transfer 2007;34:838–48.
[58] Promvonge P, Eiamsa-ard S. Heat transfer and turbulent flow friction in a circular tube fitted with conical-nozzle turbulators. International Communications in Heat and Mass Transfer 2007;34:72–82.
[59] Promvonge P, Eiamsa-ard S. Heat transfer augmentation in a circular tube using V-nozzle turbulator inserts and snail entry. Experimental Thermal and Fluid Science 2007;32:332–40.
[60] Eiamsa-ard S, Promvonge P. Experimental investigation of heat transfer and friction characteristics in a circular tube fitted with V-nozzle turbulators. International Communications in Heat and Mass Transfer 2006;33:591–600.
[61] Eiamsa-ard S, Promvonge P. Thermal characterization of turbulent tube flows over diamond-shaped elements in tandem. International Journal of Thermal Sciences 2010;49:1051–62.
[62] Anvari AR, Lotfi R, Rashidi AM, Sattari S. Experimental research on heat transfer of water in tubes with conical ring inserts in transient regime. International Communications in Heat and Mass Transfer 2011;38:668–71.
[63] Kongkaitpaiboon V, Nanan K, Eiamsa-ard S. Experimental investigation of heat transfer and turbulent flow friction in a tube fitted with perforated conical-rings. International Communications in Heat and Mass Transfer 2010;37:560–7.
[64] Meng J, Liang X, Li Z. Field synergy optimization and enhanced heat transfer by multi-longitudinal vortexes flow in tube. International Journal of Heat and Mass Transfer 2005;48:3331–7.
[65] Naphon P, Nuchjapo M, Kurujareon J. Tube side heat transfer coefficient and friction factor characteristics of horizontal tubes with helical rib. Energy Conversion and Management 2006;47:3031–44.
[66] Li X, Meng J, Guo Z. Turbulent flow and heat transfer in discrete double inclined ribs tube. International Journal of Heat and Mass Transfer 2009;52:962–70.
[67] Eiamsa-ard S, Pethkool S, Thianpong C, Promvonge P. Turbulent flow heat transfer and pressure loss in a double pipe heat exchanger with louvered strip inserts. International Communications in Heat and Mass Transfer 2008;35:120–9.
[68] Depaiwa N, Chompookham T, Promvonge P. Thermal enhancement in a solar air heater channel using rectangular winglet vortex generators. PEA-AIT Int. Conf. energy and sustainable development: Issues and strategies (ESD 2010). The Empress Hotel, Chiang Mai, Thailand. 2–4 June 2010. 1–7.
[69] Chompookham T, Thianpong C, Kwankaomeng S, Promvonge P. Heat transfer augmentation in a wedge-ribbed channel using winglet vortex generators. International Communications in Heat and Mass Transfer 2010;37:163–9.
[70] Promvonge P, Khanoknaiyakarn C, Kwankaomeng S, Thianpong C. Thermal behavior in solar air heater channel fitted with combined rib and delta-winglet. International Communications in Heat and Mass Transfer 2011;38:749–56.
[71] Promvonge P, Chompookham T, Kwankaomeng S, Thianpong C. Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators. Energy Conversion and Management 2010;51:1242–9.